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Volume I: Final Report, Task 1, Three-Dimensional Euler/Navier-Stokes Aerodynamic Method (TEAM) Enhancements

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13. ABSTRACT *(Maximum 200 words)*
McDonnell Douglas has implemented a Johnson-King turbulence model into the Wright Laboratory TEAM code. Solutions were obtained for several test cases using the standard Baldwin-Lomax model and the incorporated Johnson-King model. Comparisons with experimental data were made where possible. General agreement was seen between the two turbulence models; however, poor agreement with the experimental data was noted for the Onera M6 wing test case. Grid sensitivity studies and further calibration of the TEAM code are needed.

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FOREWORD

In accordance with the requirements of the United States Air Force contract F33615-91-C-3004 to implement the McDonnell Douglas Johnson-King turbulence model into the Air Force Wright Laboratory Three-dimensional Euler/Navier-Stokes Aerodynamic Method (TEAM), the following report was prepared by the McDonnell Douglas Research Laboratory (MDRL), St. Louis, Missouri, for the Aeromechanics Division of Wright Laboratory. The contract monitor for this program was Captain Keith B. Jochum, and Dr. Raymond Cosner, McDonnell Aircraft Company, was the McDonnell Douglas program manager. Dr. Ramesh Agarwal (MDRL) was the principal investigator and Dr. Thomas Gielda (MDRL) provided technical assistance. Additional programming support was provided by Mr. Steve Ellison of the McDonnell Douglas Missile System Company (MDMSC). McDonnell Douglas acknowledges the assistance of Captain Jochum and Dr. Don Kinsey for their interest and support during the contract performance period.

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1.0 INTRODUCTION

The purpose of this investigation was to improve the prediction capability of Wright Laboratory Three-Dimensional Euler/Navier-Stokes Aeromechanic Method, designated TEAM, through the implementation of the McDonnell Douglas nonequilibrium Johnson-King (J-K) turbulence model. The J-K turbulence model has been demonstrated to predict more accurately surface pressure distributions on supercritical transonic airfoils and wings with small regions of axially shock-separated flow. The following subsections will provide a brief history of the development, calibration and limitations of the J-K model.

1.1 MDC Johnson-King Turbulence Model

The McDonnell Douglas Research Laboratory has developed a three-dimension nonequilibrium Johnson-King turbulence model in support of the ongoing Delta rocket program at the McDonnell Douglas Space Systems (MDSSC) Company, Huntington Beach, California. The J-K model was developed to predict more accurately the surface pressure distributions on the large payload variants of the Delta rocket. The increased payload Delta forebody configuration included a boat-tail region which was susceptible to shock-wave-boundary-layer separation.

Numerical simulations of the increased payload Delta flowfield with the standard Baldwin-Lomax (B-L) turbulence model underpredicted the extent of the axial separation bubble. To overcome this deficiency, the J-K formulation of Abid and Johnson [1] was implemented. Simulations were performed on the Delta N1B1 forebody configuration, shown in Figure 1.1.1, with the Baldwin-Lomax and Johnson-King and k-ε turbulence models. Figure 1.1.2 depicts the computed surface pressure on the N1B1 forebody. Note the improved agreement with the experimental data that the J-K and k-ε models provide. The J-K formulation developed for the Delta program has been modified for implementation into the TEAM code.

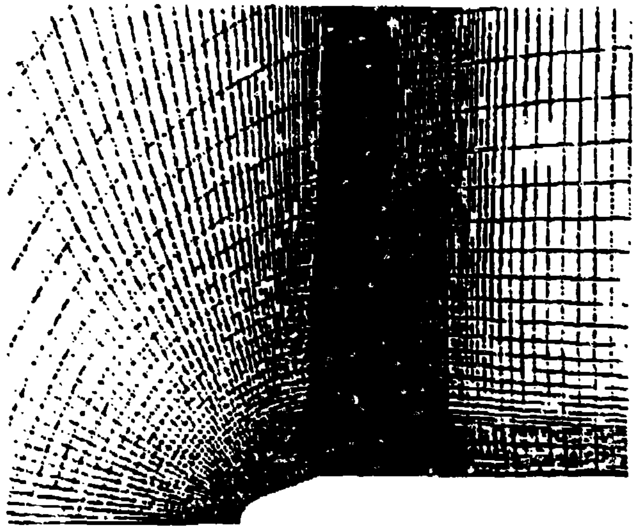


Figure 1.1.1. Comuptational Grid for Delta N1B1 Forebody Simulation

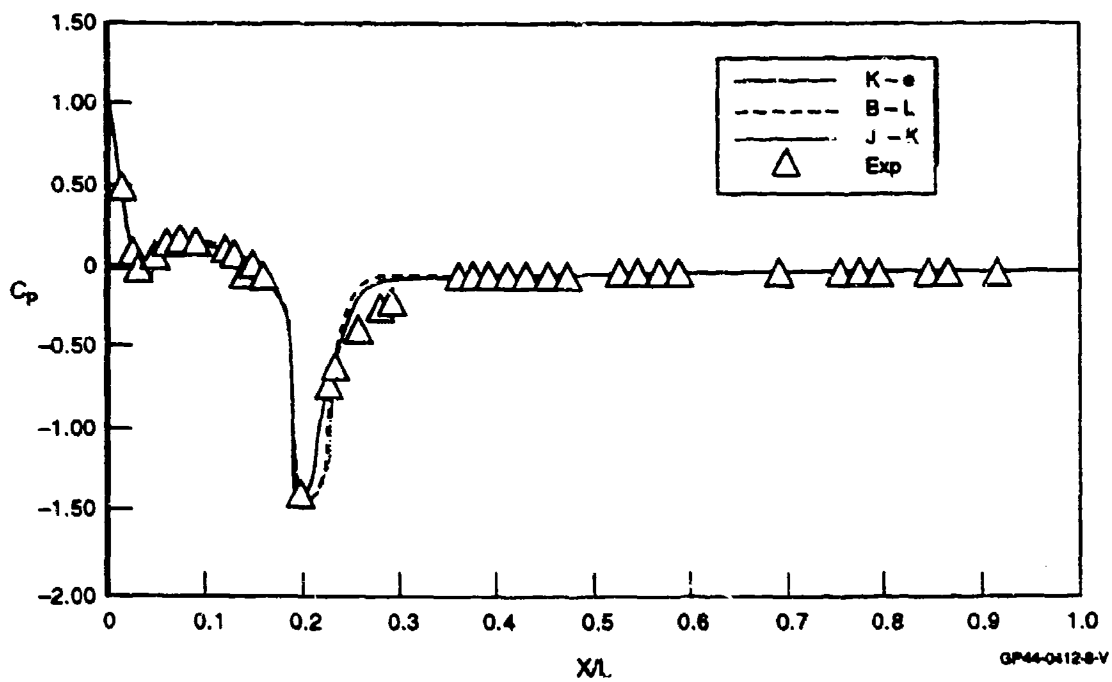


Figure 1.1.2. Comparison of Computed and Measured Surface Pressure on the M1B1 Forebody for the MDC Johnson-King, Baldwin-Lomax and K-e Turbulence Models; $M_\infty = 0.8$, $\alpha = 0.0$, Rc = 4,000,000.0/ft.

1.2 MDC Johnson-King Team Code Calibration Plan

To demonstrate the J-K implementation into the TEAM code several test cases were computed. The test case configurations were: (1) a simple flat plate, (2) the RAE 2822 airfoil, and (3) the Onera M6 wing. The test cases were chosen to provide an increasing level of geometric complexity. For all test cases the analyses were conducted with both the B-L and J-K turbulence models. Comparisons were made with existing experimental data where possible.

1.3 Turbulence Model Formulation Limitations

The J-K model installed into the TEAM code has one limitation which was resulting from the scope of the contract as spelled out in the statement-of-work. The J-K model in the TEAM code has been coded for configurations where the solid walls correspond to a k=1 surface. The J-K model is functional for zonal geometries; however, as specified above, the solid walls must lie on a K=1 surface.

2.0 GOVERNING EQUATIONS

In the following sections the development of the MDC J-K model will be discussed.

2.1 Johnson-King Turbulence Model Formulation

In this investigation, the J-K formulation of Abid and Johnson [1] was employed. A summary of their model follows.

In the Johnson-King nonequilibrium model the functional form of the eddy viscosity is:

$$\mu_t = \mu_{to}\left(1 - e^{\frac{-\mu_{ti}}{\mu_{to}}}\right) \tag{1}$$

The inner viscosity, μ_{ti}, is defined by the following:

$$\mu_{ti} = \varrho\, D^2\, \varkappa\, N\, \tau_m^{\frac{1}{2}} \tag{2}$$

where τ_m is the maximum Reynolds shear stress, N is the body normal distance and $\varkappa$ is the von Karman constant ($\varkappa = 0.4$). The damping coefficient D is defined by the following expression:

$$D = \left(1 - e^{\frac{y+}{A+}}\right) \tag{3}$$

where $A^+ = 17$ and y^+ is the standard law-of-the-wall coordinate. The Reynolds shear stress is assumed to be of the form:

$$\tau_m = \frac{\mu_t |\omega|}{\varrho} \tag{4}$$

where ω is the magnitude of the vorticity, and the variable τ_m is determined from the solution of a partial differential equation which will be described below.

The outer eddy viscosity μ_{to} is found from the equation below:

$$\mu_{to} = \varrho\, \sigma\, K\, C_c\, F_w\, \gamma_k \tag{5}$$

where:

$K = 0.0168$

$C_c = 1.6$

$F_w = N_{max} F_{max}$

F_{max} is the maximum of the function:

$$F(N) = N \; D^{k|\omega|} \tag{6}$$

and N_{max} is the body-normal distance to the point where F(N) is a maximum. Intermittency effects are modeled by:

$$\gamma_k = \left[1.0 + 5.5 \left(\frac{0.3 \; N}{N_{max}} \right)^6 \right]^{-1} \tag{7}$$

The variable $\overline{\sigma}$ provides the link between the eddy viscosity distribution and the variable τ_m. If one assumes that the ratio of Reynolds shear stress to the turbulent kinetic energy is constant at the location where τ_m occurs, a partial differential equation for τ_m can be derived from the turbulent kinetic energy equation. Complete details of the derivation are give in reference [2]. In the cartesian coordinate frame this equation can be written as:

$$\frac{\partial \tau_m}{\partial t} + U_m \frac{\partial \tau_m}{\partial x} + V_m \frac{\partial \tau_m}{\partial y} + W_m \frac{\partial \tau_m}{\partial z} = \frac{a_1 \; \tau_m}{L_m} \left(\tau_{m,eq}^{\frac{1}{2}} - \tau_m^{\frac{1}{2}} \right) - a_1 \; D_m \tag{8}$$

The subscript m denotes the variable is evaluated at a point where the τ_m is a maximum. The dissipation length scale L_m is defined as:

$$L_m = \min \; (0.4 \; N_m, \; 0.09 \; \delta) \tag{9}$$

where δ is the boundary layer thickness and assumed to be 1.9 N_{max}. $\tau_{m,eq}$ is the value of τ_m assuming that eddy viscosity profile is in equilibrium (i.e., $\overline{\sigma} = 1.0$). The diffusion term D_m, modeled by Johnson [3], is defined as:

$$D_m = \frac{C_D \, \tau_m^{\frac{3}{2}} \left| 1 - \overline{\sigma}^{\frac{1}{2}} \right|}{a_1 (0.7 \, \delta - N_m)} \tag{10}$$

Throughout this investigation the values of a_1 and C_d were fixed at 0.25 and 0.5, respectively.

In order to simplify the partial differential equation a change of variables was made. Let:

$$g = \tau_m^{\frac{-1}{2}}$$
$$g_{eq} = \tau_{m,eq}^{\frac{-1}{2}} \tag{11}$$

The transformed PDE becomes:

$$\frac{\partial g}{\partial t} + U_m \frac{\partial g}{\partial x} + V_m \frac{\partial g}{\partial y} + W_m \frac{\partial g}{\partial z} + \Gamma = 0 \tag{12}$$

where:

$$\Gamma = \frac{a_1}{2 \, L_m} \left[\left(\frac{g}{g_{eq}} - 1 \right) - \frac{C_D \, L_m \left| 1 - \overline{\sigma}^{\frac{1}{2}} \right|}{a_1 \, \delta \left(0.7 - \frac{N_m}{\delta} \right)} \right] \tag{13}$$

The above equation is then transformed to the computational plane to simplify the integration. A further simplification is made by assuming steady flow. The simplified transformed equation becomes:

$$\left[u_m \, \varepsilon_x + v_m \, \varepsilon_y + w_m \, \varepsilon_z \right] \frac{\partial g}{\partial \varepsilon} +$$
$$\left[u_m \, \zeta_x + v_m \, \zeta_y + w_m \, \zeta_z \right] \frac{\partial g}{\partial \zeta} + \Gamma = 0 \tag{14}$$

Note that ε and ζ directions correspond to the transformed streamwise and spanwise directions, respectively. The terms containing the transformed normal derivative (η) were assumed to be negligible along the surface where τ_m occurs. For complete details see reference [4]. The above equation can now be solved for g and subsequently τ_m. Once τ_m is known, a new value of sigma is computed from:

$$\overline{\sigma}^{n+1} = \overline{\sigma}^{n} \frac{\varrho_{max} \, \tau_m}{\left(\mu_t |\omega| \right)_{max}} \tag{15}$$

2.2 Solution Procedure

The partial differential equation for g (14) was integrated via successive-line-over-relaxation. Line relaxation was performed in the transformed streamwise (ξ) direction. The cross-flow derivative (ζ) terms were treated as source terms and moved to the right-hand side of the equation. By solving the equation for g in this manner overall CPU time expenditures were reduced.

When the TEAM code is initialized the values of $\overline{\sigma}$ are set to 1.0. Once the solution has been advanced in time, the JKTM subroutine writes out the current values of $\overline{\sigma}$ and g to I/O unit 55 (i.e., fort.55). This data file is required for subsequent restarts. If the fort.55 data file is not present, the JKTM subroutine defaults the value of $\overline{\sigma}$ back to 1.0.

3.0 MDC MODIFICATIONS TO TEAM

To complete the installation of the J-K module into the TEAM code, four subroutines were added to the original TEAM software. Subroutines JKEXEC, JKSET, JKTM and THOMAS are discussed below. Also, a minor modification was made in subroutine FILTER to allow the J-K model to be called from the main program driver.

To invoke the J-K turbulence model the turbulence model selection term, in the auxiliary data set, is set from "bltm" to "jktm." Once the selection term is set to "jktm," the TEAM code will invoke the J-K turbulence model.

3.1 Subroutine JKEXEC

Subroutine JKEXEC prepares the data set to be fed into the J-K turbulence model. The function of JKEXEC is to search through the boundary condition table to locate the viscous wall and pass the variables to subroutine JKSET.

3.2 Subroutine JKSET

Subroutine JKSET converts the flow and grid data passed from JKEXEC into the form required by the subroutine JKTM. JKSET converts the cell-centered to cell-face flow variables. Once the data conversion is complete, subroutine JKSET then calls subroutine JKTM.

3.3 Subroutine JKTM

Subroutine JKTM computes the turbulent eddy viscosity in a manner as described in Section 2.0.

3.4 Subroutine THOMAS

Subroutine Thomas performs a tridiagonal inversion required by subroutine JKTM.

4.0 TEAM CODE CALIBRATION TEST CASES

To meet the contractual obligation of the statement of work, MDC performed a series of code calibration runs to demonstrate the installation of the J-K turbulence model into the TEAM code. The computed test cases were:

1a -- Flat plate with B-L turbulence model,	(Required by Contract)
1b -- Flat plate with J-K turbulence model,	(Required by Contract)
2a -- RAE 2822 Airfoil with B-L turbulence model,	(MDC Optional)
2b -- RAE 2822 Airfoil with J-K turbulence model,	(MDC Optional)
3a -- Onera M6 wing with B-L turbulence model, and	(Required by Contract)
3b -- Onera M6 wing with J-K turbulence model.	(Required by Contract)

4.1 Flat Plate

Test cases 1a and b were computed to demonstrate the implementation of the J-K turbulence model into the TEAM code. The freestream conditions employed for this test case were:

$M_\infty = 0.7$ $\quad\quad$ $Re = 1{,}000{,}000$

The computational grid consisted of 101 streamwise by 61 normal by 3 spanwise grid points. A comparison of the theoretical and computed skin-friction coefficient for both the B-L and J-K turbulence models is shown in Figure 4.1.1. Note the generally poor agreement with the empirical result of van-Driest. Instead of decreasing monotonically down the plate, the values of C_f increase near the exit of the computational domain. This behavior indicated that the TEAM code did not have the capability to accurately model near-field subsonic outflow.

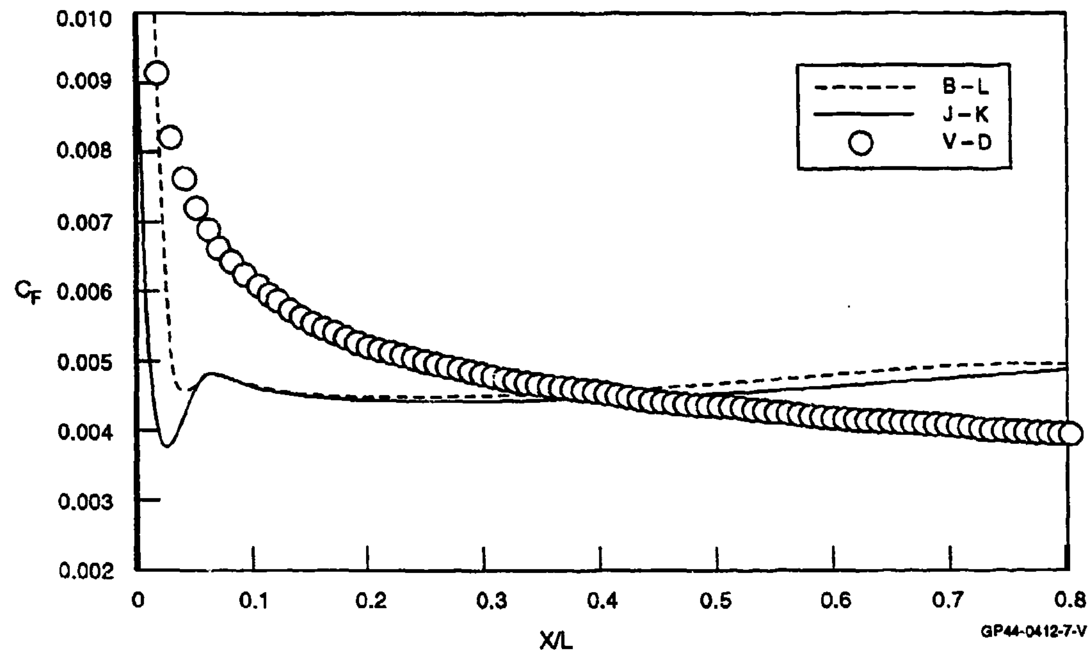


Figure 4.1.1. Comparison of computed and theoretical skin-friction coefficient for a flat plate with the Baldwin-Lomax and Johnson-King turbulence Models; $M_\infty = 0.7$, Re = 1,000,000.0.

4.2 RAE 2822 Airfoil

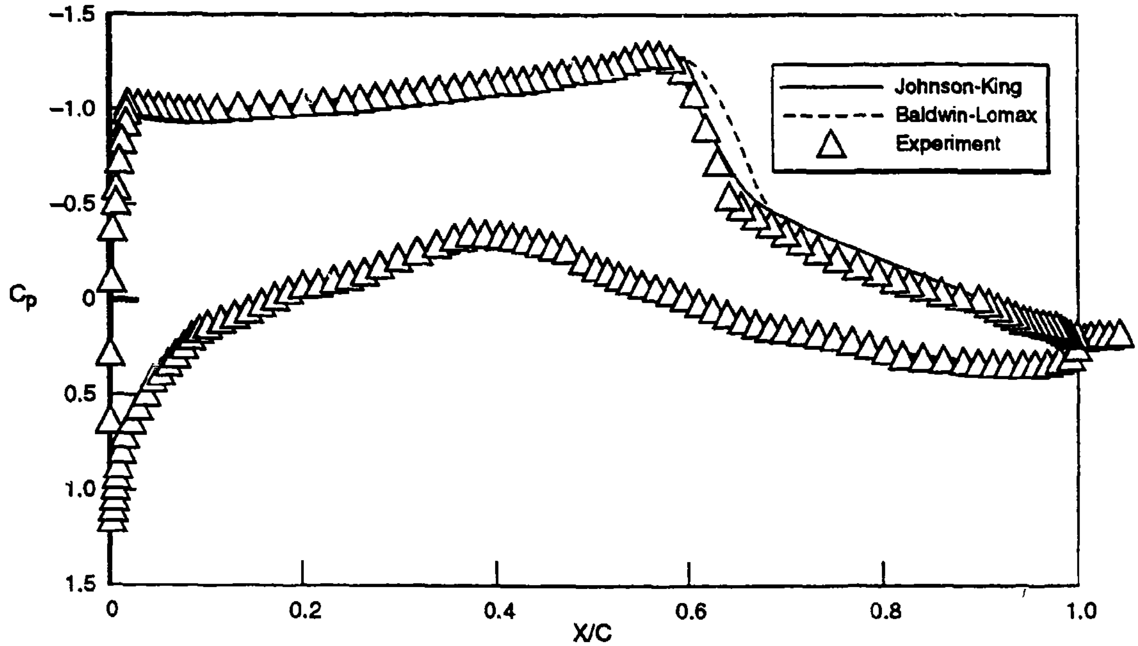
Test cases 2a and 2b demonstrated the capability of the J-K model to compute two-dimensional transonic flow over a supercritical airfoil section. The computational grid consisted of 241 streamwise by 65 normal by 2 spanwise grid points. The freestream conditions for this test case are shown below:

$M_\infty = 0.75$ $\alpha = 2.8$ Degrees

$Re_c = 6.2 \times 10^6$

Grid point spacing in the normal direction was maintained such that the y^+ value for the first point off the wall did not exceed 4.0. The TEAM code default options were used for time step and dissipation.

Comparisons of computed and measured surface pressure coefficients are made, with good agreement, in Figure 4.2.1. The J-K solution more accurately predicts the shock-wave location on the suction-surface of the airfoil. Both the B-L and J-K solutions were run for approximately 2500 iterations and 4 orders of magnitude reduction of the L2 norm was obtained.



GP44-0412-6-V

Figure 4.2.1. Comparison of the Computed and Measured Surface Pressure Coefficient on the RAE 2282 Airfoil; $M_\infty = 0.75$, $\alpha = 2.8$ Deg., Re = 6,200,000.

4.3 Onera M6 Wing

Test cases 3a and b demonstrated the capability of the J-K model to compute three-dimensional transonic flow over wing configurations. The computational grid for the ONERA M6 wing consisted of 193 streamwise by 36 normal by 37 spanwise grid points. The freestream conditions for this test case are shown below:

$M_\infty = 0.84$ $\alpha = 3.06$ Degrees

$Re_c = 11.7 \times 10^6$

Grid point spacing in the normal direction was maintained such that the y^+ value for the first point off the wall did not exceed 10.0.

Comparisons of computed and measured surface pressure coefficients are made, at the spanwise locations of (z/b) = 0.2, 0.45, 0.65, 0.90 and 0.95 in Figures 4.3.1,2,3,4 and 5, respectively. The agreement of the B-L and J-K computed solutions is good; however, the comparison with the experimental data is poor.

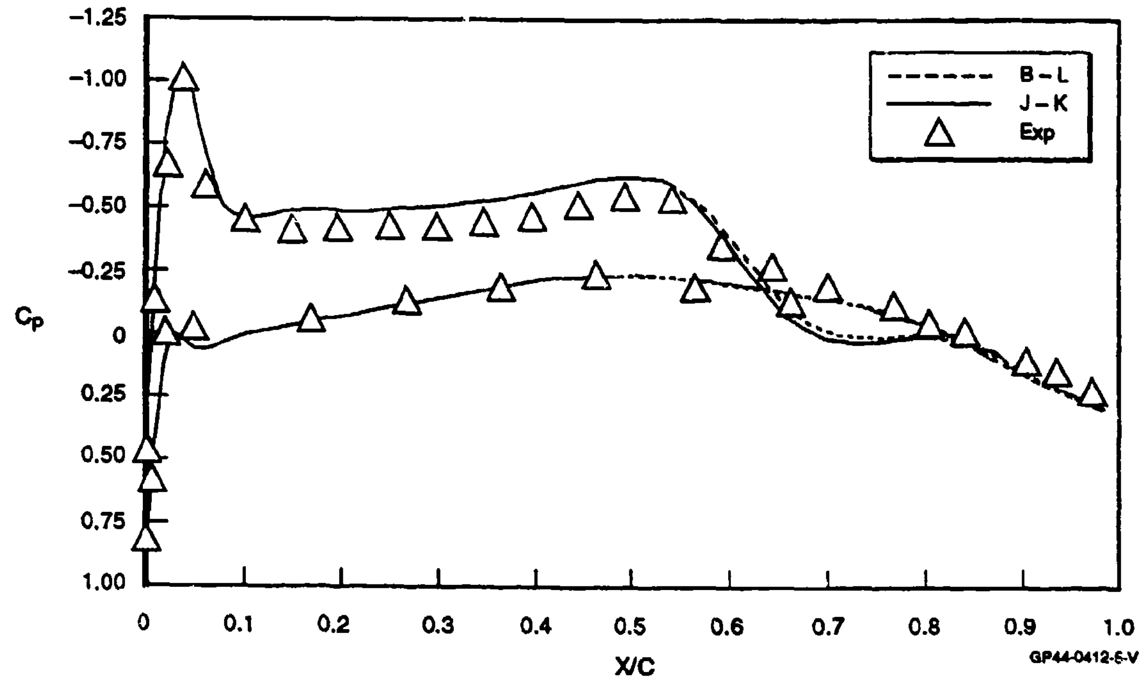


Figure 4.3.1. Comparison of the Computed and Measured Surface Pressure Coefficient on the Onera M6 Wing at the y/b = 0.20 Span Station; M∞ = 0.84, α = 3.0 Deg., Re = 11,700,000.0.

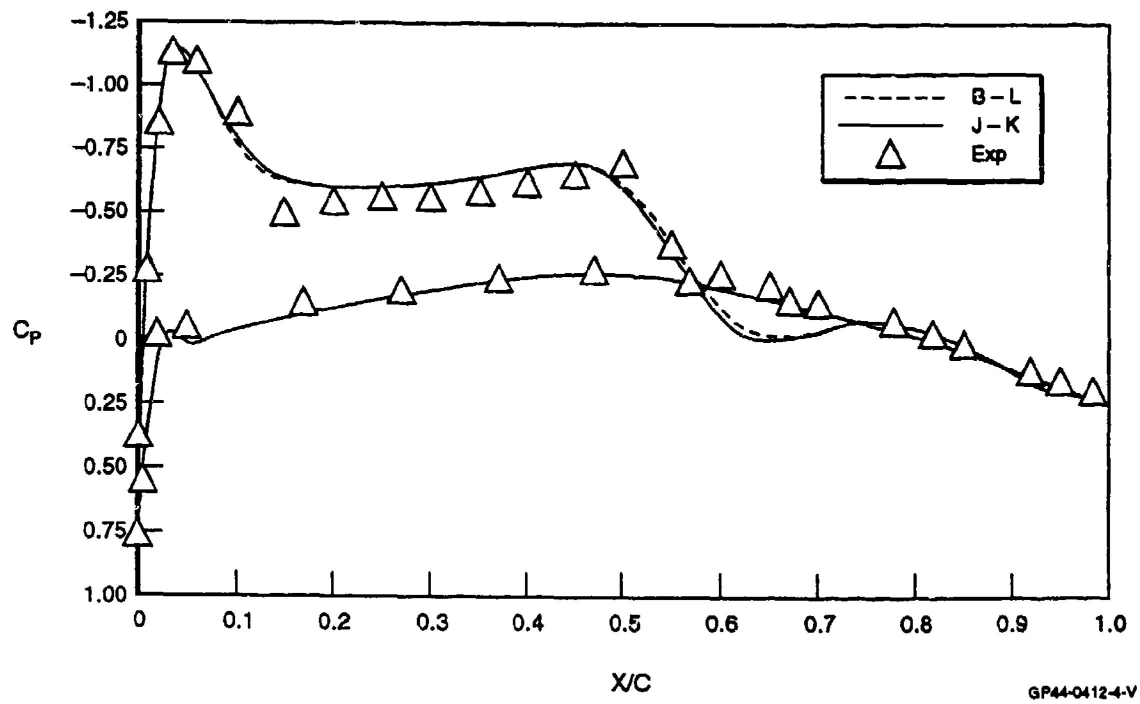


Figure 4.3.2. Comparison of the Computed and Measured Surface Pressure Coefficient on the Onera M6 Wing at the y/b = 0.45 Span Station; M∞ = 0.84, α = 3.0 Deg., Re = 11,700,000.0.

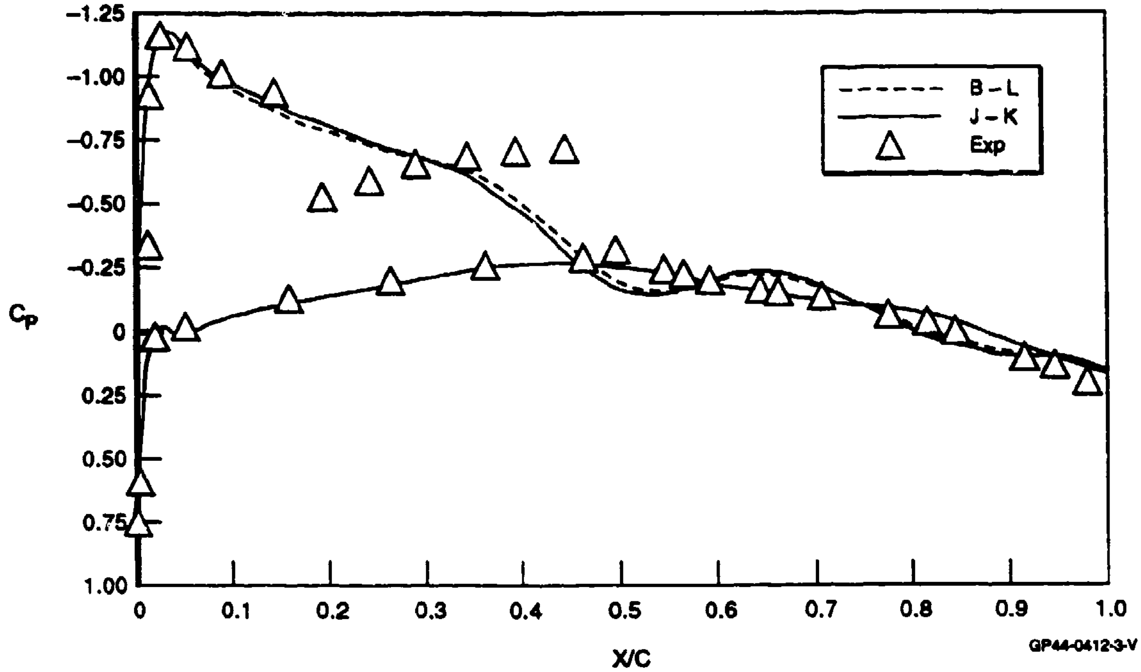


Figure 4.3.3. Comparison of the Computed and Measured Surface Pressure Coefficient on the Onera M6 Wing at the y/b = 0.65 Span Station; M∞ = 0.84, α = 3.0 Deg., Re = 11,700,000.0.

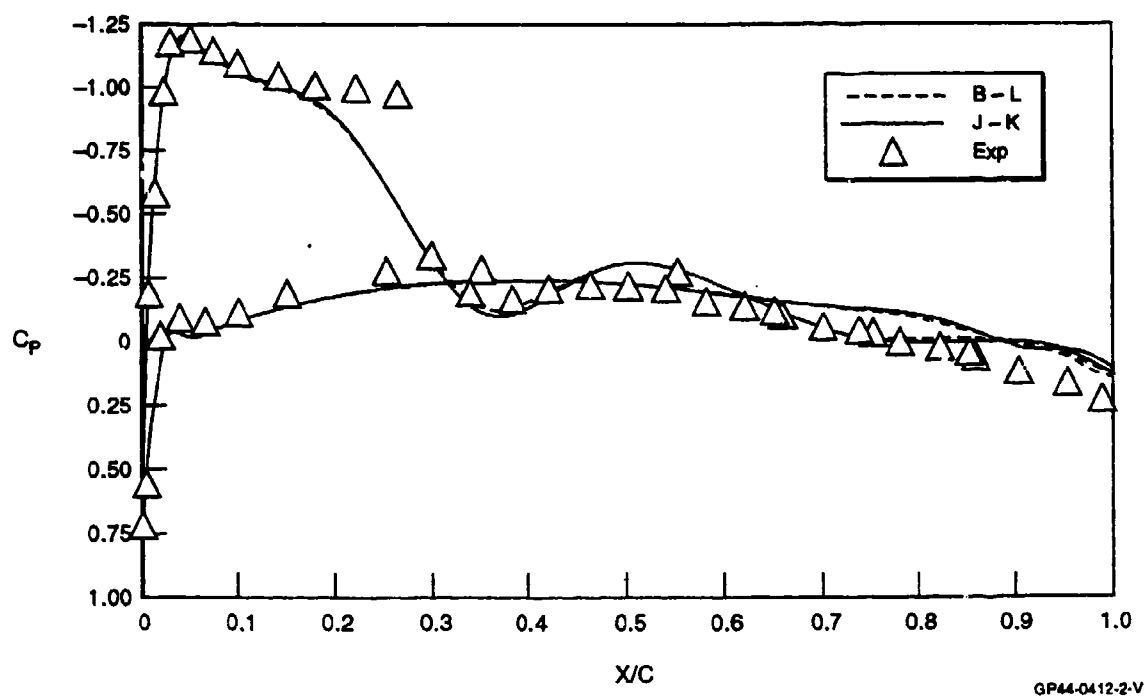


Figure 4.3.4. Comparison of the Computed and Measured Surface Pressure Coefficient on the Onera M6 Wing at the y/b = 0.90 Span Station; M∞ = 0.84, α = 3.0 Deg., Re = 11,700,000.0.

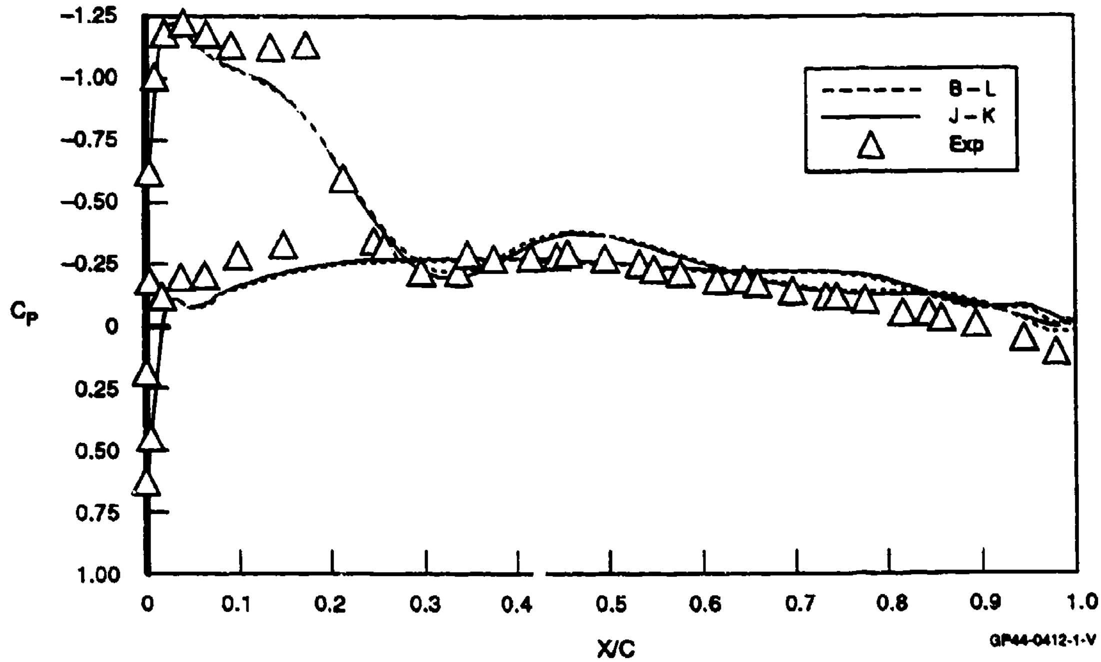


Figure 4.3.5. Comparison of the Computed and Measured Surface Pressure Coefficient on the Onera M6 Wing at the y/b = 0.95 Span Station; M_∞ = 0.84, α = 3.0 Deg., Re = 11,700,000.0.

Poor agreement with the experimental data was attributed to the fact that the computational grid did not have the sufficient density, in the streamwise direction, to capture the shock-wave adequately on the suction surface. Grid density studies were required but not possible due to the scope of the contract statement-of-work.

All input data files required for the ONERA Wing simulation are listed the Appendix.

4.4 Discussion

MDC has implemented a J-K model into the TEAM code. Computations have been performed for both 2-D flat plate, 2-D airfoil, and 3-D wing configurations. Computed solutions from the B-L and J-K turbulence models appear to be in reasonable agreement; however, for the case of the ONERA M6 wing, the agreement between the computed solutions and the experimental data is poor. Poor agreement with the ONERA data is attributed to inadequate grid resolution on the suction side of the airfoil in the recompression region. Further calibration of the TEAM code is indicated, but not covered in the scope of this investigation.

5.0 REFERENCES

[1] Abid, R. and Johnson, D. A., "Effects of Turbulence Models on the Prediction of Transonic Wing Flows," AIAA Paper 89-2224, 1986.

[2] Abid, R., Vatsa, V. N., Johnson, D. A. and Wedan, B. W., "Prediction of Separated Transonic Wing Flows with a Non-Equilibrium Algebraic Model," AIAA Paper 89-0558, 1989.

[3] Johnson, D. A. and King, L. S., "A Mathematically Simple Turbulent Closure Model for Attached and Separated Turbulent Boundary Layers," AIAA Journal, Vol. 23, No 11, pp.1684-1692, 1985.

[4] Yu, N. J., Allmaras, S. R. and Moschetti, K. G., "Navier-Stokes Calculations for Attached and Separated Flows Using Different Turbulence Models," AIAA Paper 91-1791, 1991.

6.0 APPENDICES

Main Program Control Input Data Set

Auxiliary Input Data Set

'zone 1' '__tm' 0

'zone 1' 'segment' 1

29 165 4 5 1 1

'zone 1' 'segment' 1

29 165 8 9 1 1

'zone 1' 'segment' 1

29 165 13 14 1 1

'zone 1' 'segment' 1

29 165 16 17 1 1

'zone 1' 'segment' 1

29 165 19 20 1 1

'zone 1' 'segment' 1

29 165 21 22 1 1

'zone 1' 'segment' 1

26 165 24 25 1 1

Boundary Condition Data Set

'zone 1' '_ree' 'tlns-k' 9

1	1	1	37	1	33	'far'
193	193	1	37	1	33	'far'
29	165	1	25	1	1	'solid'
1	29	1	25	1	1	'wake'
193	165	1	25	1	1	'zone 1'
165	193	1	25	1	1	'wake'
29	1	1	25	1	1	'zone 1'
1	193	25	37	1	1	'wake'
193	1	25	37	1	1	'zone 1'
1	193	1	1	1	33	'symmetry_xz'
1	193	37	37	1	33	'far'
1	193	1	37	33	33	'far'